

# SNAPSHOT IMAGING SPECTROPOLARIMETER FOR THE LONG WAVELENGTH INFRARED

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## ABSTRACT

An extremely unique imaging system, that is capable of simultaneously recording both the spectral and polarimetric signatures of all the spatial locations/targets in a scene with just a single integration period of a camera, has been built for use in the long wavelength infrared, 8 to 12 microns. The system contains no moving parts and collects all of its data in a single snapshot. This snapshot capability makes it ideally suited for observing and characterizing quick events or fast moving objects without the associated scanning artifacts found in conventional imaging spectrometers and polarimeters. The rate at which you can record the temporal nature of a target's spectral and polarimetric signature is only limited by the frame rate and sensitivity of the camera detector.

## OVERVIEW

The imaging system is based on a combination of a Computed Tomographic Imaging Spectrometer (CTIS) and a channeled spectropolarimeter. Only three polarization elements need to be added to a CTIS system to incorporate channeled spectropolarimetry, but to understand how the entire spectropolarimeter system works we will first review the basic design and operating principles of the Computed Tomographic Imaging Spectrometer (CTIS).

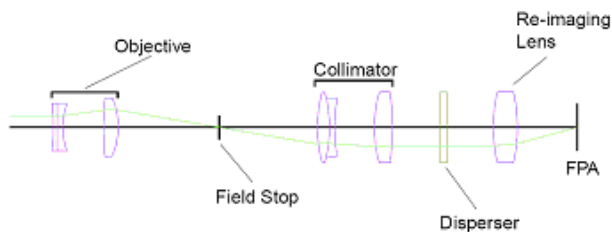


Figure 1: Optical layout for CTIS.

The optical layout for a CTIS system, shown above, is similar to that of a conventional camera, but

instead of putting a focal plane at the image after the objective lens, a small square aperture or field stop is placed at this image location. The light from this intermediate image is then collimated by another lens and passed through a specially designed computer generated hologram or disperser. The computer generated hologram is a custom two-dimensional diffraction grating specially designed to only send light into a 5x5 grid of diffraction orders as illustrated in figure 2. The light from the zero order, which is not diffracted by the CGH, forms a panchromatic image of the scene at the center of the focal plane. The size of this zero order will determine the spatial resolution of the system. Light in the outer diffraction orders will map the various spectral components of the scene to different spatial locations on the focal plane. These monochromatic images of the scene overlap each other forming a "spectral smear" of the scene in each of the outer diffraction orders on the recorded image.

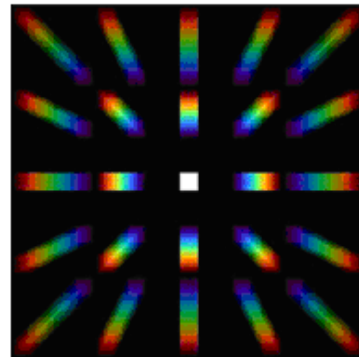


Figure 2: Example of recorded image of a broadband white light source recorded by a visible CTIS system.

Each of these diffraction orders can be considered as a projection of a three-dimensional object cube ( $x, y$ , and  $\lambda$  in height) onto the two-dimensional focal plane at various angles. By using the same reconstruction techniques as those used in medical tomography, such as

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Expectation Maximization (EM) or Multiplicative Algebraic Reconstruction Technique (MART), we can analyze the 2D projections/diffraction orders recorded on the FPA to reconstruct an estimate of the original 3D object cube of the scene. This reconstruction of the 3D object cube ( $x, y, \lambda$ ) allows the CTIS to determine the spectral data at each spatial position of the scene based on the single snapshot image recorded by the system. Shown below are some results from the constructed LWIR CTIS system.

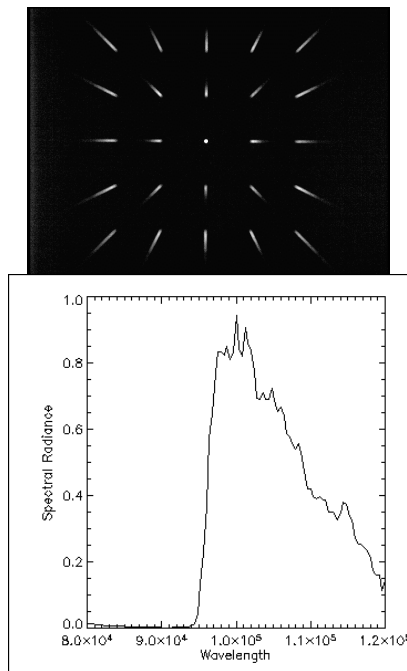


Figure 3: (top) The raw image captured by the LWIR CTIS when viewing a 1000 degree C blackbody through a 9.4 micron cut on spectral filter. (bottom) The spectral reconstruction of the filtered blackbody object clearly showing the spectral characteristics of the combined blackbody and high pass spectral filter.

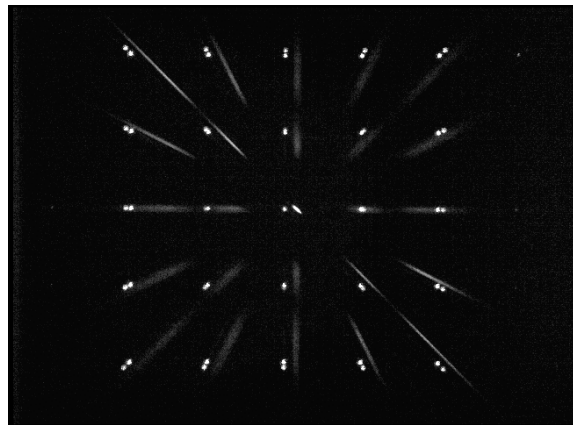


Figure 4: The raw CTIS image viewing the tip of a soldering iron and output of a CO<sub>2</sub> laser

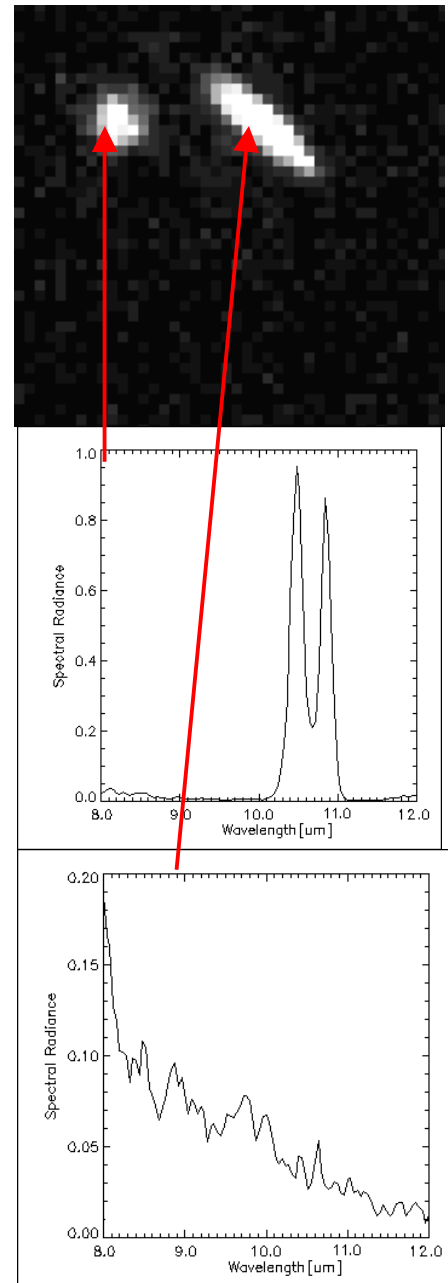


Figure 5: (top) Close up of the zero order image from figure 4. (middle) The spectral reconstruction of light from the CO<sub>2</sub> laser. The light output from the laser wasn't stable, and the lasing wavelength of the laser would vary in time. In this instance you can see that the laser was actually lasing in two spectral modes. This multimode operation of the laser only occurred for a brief period of time, providing an excellent demonstration of the snapshot capability of the CTIS system. (bottom) The blackbody like spectral output from the tip of the soldering iron.

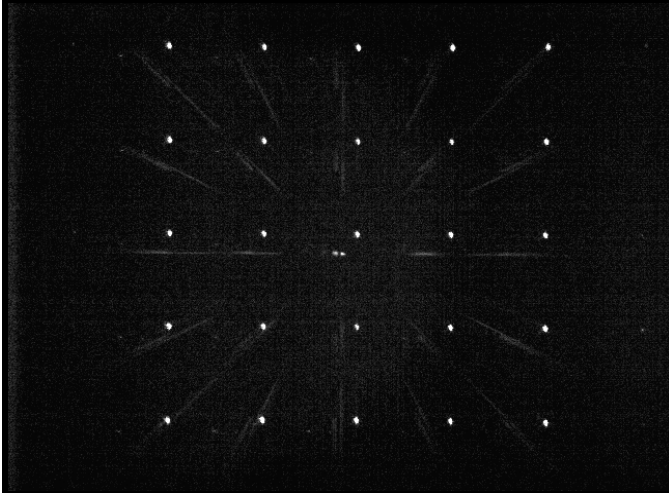


Figure 6: The raw CTIS image viewing CO2 laser light and the tip of a soldering iron where part of the soldering iron is covered by a 9.4 micron cut on spectral filter

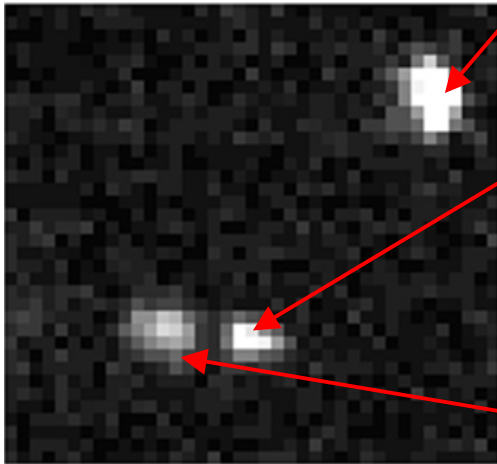


Figure 7: Zero order image from figure 6 showing the three targets in the scene: soldering iron, spectrally filtered soldering iron, and CO2 laser. Spatially all of the targets look similar and are not clearly identifiable. With just this single frame of data the CTIS system can reconstruct the spectrum from all the spatial locations in the scene allowing in the identification of the three targets.

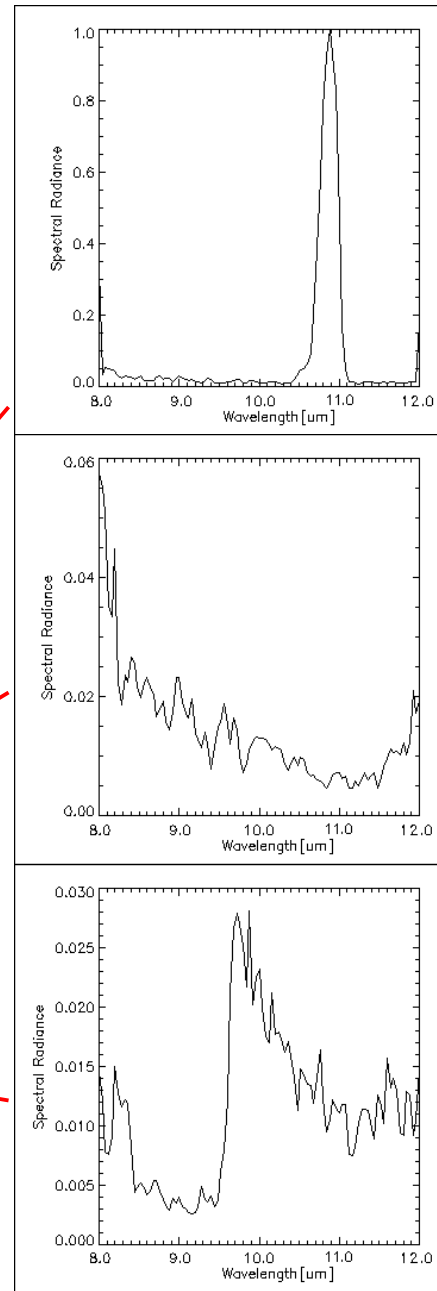


Figure 8: (top) The spectral reconstruction of this object/spatial location clearly shows a strong monochromatic light output, indicating that this target is the output from the CO2 laser. (middle) The blackbody like spectral output is from the unfiltered tip of the soldering iron. Note that the data points at the extremes of the spectrum suffer from artifacts of the iterative tomographic reconstruction process. (bottom) The spectral reconstruction of this point clearly shows that this was the part of the soldering iron covered by the spectral filter. You can clearly see the spectral features due to the filter.

## INCORPORATING CHanneLED SPECTROPOLARIMETRY

To incorporate channeled spectropolarimetry into a CTIS system only three polarization elements need to be added, which can be seen in figure 9. The added elements are placed in the collimated space of the CTIS, before the CGH, and consist of two thick birefringent crystal retarders, with their fast axes oriented at 0 and 45 degrees respectively, and an analyzing polarizer oriented at 0 degrees. These added components will encode the polarization information of the light into intensity modulations across the spectra. By carefully analyzing these recorded intensity modulations we will be able to reconstruct all four Stokes components for all of the wavelength bands, for each spectrum from all the spatial locations in the scene, all with just a single frame of data. We refer to this combined system as a Computed Tomographic Imaging Channeled Spectropolarimeter (CTICS).

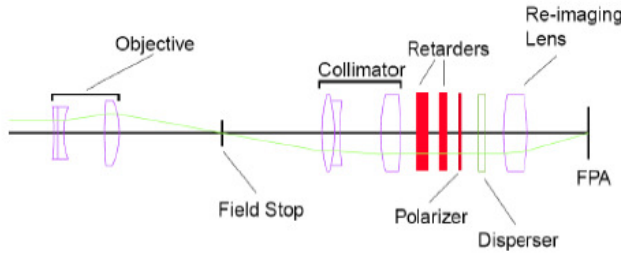


Figure 9: Optical layout for CTICS

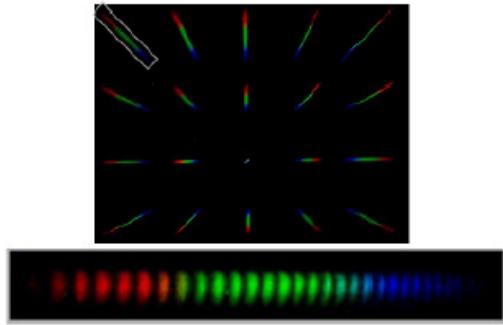


Figure 10: Example of modulated spectra recorded when viewing a polarized broadband object with a visible CTICS system.

We can see how the spectral dependence of the Stokes components are encoded into intensity modulations in the spectra by carefully analyzing the added components of the system. Mueller matrices and Stokes vectors provide an ideal way to analyze the electric field output of the light leaving the set of polarization elements. The following equation uses the Mueller matrices for the added optical elements to determine the

Stokes vector output from the elements with an arbitrary polarization input.

$$\mathbf{s}_{out} = \begin{pmatrix} 1/2 & 1/2 & 0 & 0 \\ 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\delta_2) & 0 & -\sin(\delta_2) \\ 0 & 0 & 1 & 0 \\ 0 & \sin(\delta_2) & 0 & \cos(\delta_2) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\delta_1) & \sin(\delta_1) \\ 0 & 0 & -\sin(\delta_1) & \cos(\delta_1) \end{pmatrix} \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix}$$

Note that  $\delta_1$  and  $\delta_2$  correspond to the retardance of the first and second optical retarders, and that both of these quantities vary as a function of wavelength. Specifically the retardance is given by:

$$\delta = 2\pi \cdot d \cdot \Delta n \cdot (1/\lambda)$$

Where  $d$  is the thickness of the material and  $\Delta n$  is the difference in index of the ordinary and extraordinary axes of the material at the given wavelength  $\lambda$ . The quantity  $1/\lambda$  is equal to the wavenumber of light and is often expressed with the symbol  $\sigma$ .

Multiplying the matrices reveals that the output Stokes vector is given by:

$$\mathbf{s}_{out} = 1/2 \begin{pmatrix} s_0 + s_1 \cos(\delta_2) + s_2 \sin(\delta_1) \sin(\delta_2) - s_3 \cos(\delta_1) \sin(\delta_2) \\ s_0 + s_1 \cos(\delta_2) + s_2 \sin(\delta_1) \sin(\delta_2) - s_3 \cos(\delta_1) \sin(\delta_2) \\ 0 \\ 0 \end{pmatrix}$$

Since the detector itself is only sensitive to intensity and not to a particular polarization state, it only responds to the first component of the Stokes vector, which corresponds to the total intensity of the light leaving the polarizer. This recorded intensity is a function of wavelength/wavenumber and is given by the equation:

$$2I(\sigma) = s_0 + s_1 \cos(\delta_2) + s_2 \sin(\delta_1) \sin(\delta_2) - s_3 \cos(\delta_1) \sin(\delta_2)$$

This equation describes how the addition of the two retarders and polarizer allow the four Stokes components, which also vary as a function of wavenumber, to be encoded as intensity modulations in the recorded spectra. Consider the case where you are imaging a spectrally uniform, broadband point object that is horizontally polarized across the entire spectrum ( $s_0 = 1$ ,  $s_1 = 1$ ,  $s_2 = 0$ ,  $s_3 = 0$ ). You can see from the equation that the intensity modulation will vary as the cosine of the retardance of the second retarder, which is linear with wavenumber. If the polarization properties of the object were different, the resulting modulations in the spectra would also be different, given by the previous equation. These modulations will appear in the diffraction orders of the CTICS system as shown in the following figure.



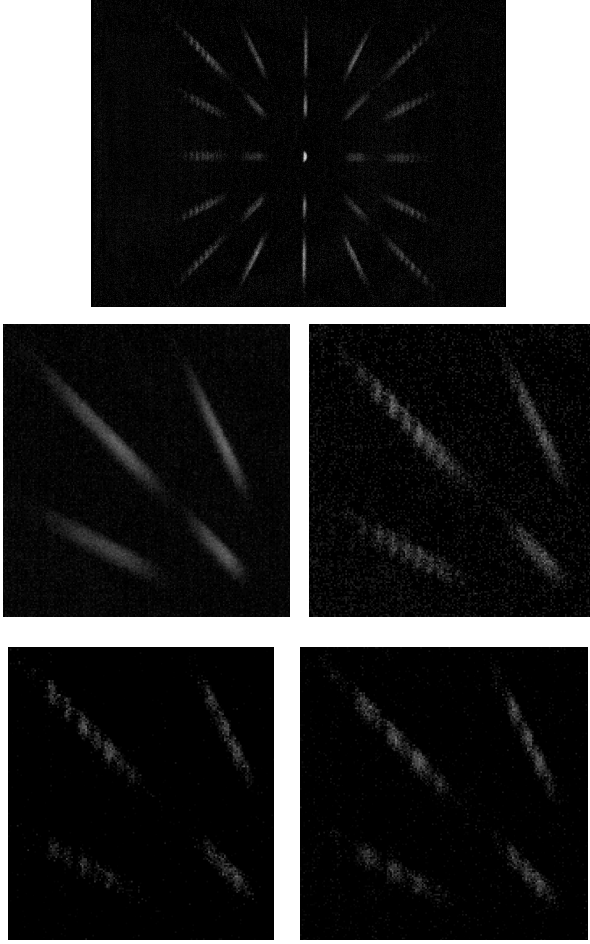


Figure 11: (top) Raw image acquired by LWIR CTICS when viewing a horizontally polarized blackbody object. Note the intensity modulations in the spectra for each of the diffraction orders (bottom) Zoomed in image of diffraction orders demonstrating how the modulation changes depending upon objects polarization state; unpolarized (middle left), horizontally polarized (middle right), vertically polarized (bottom left), and linearly polarized at 45 degrees (bottom right).

In order to reconstruct the four stokes components for all the wavelength bands of a recorded modulated spectrum, we first use Euler's identity to rewrite the equation describing the spectral intensity modulation function, which is rewritten below.

$$I(\sigma) = \frac{1}{2}s_0 + \frac{1}{4}s_1(e^{i\delta_2} + e^{-i\delta_2}) + \frac{1}{8}[(s_2 - is_3)e^{i(\delta_2 + \delta_1)} + (s_2 + is_3)e^{-i(\delta_2 + \delta_1)} + (-s_2 - is_3)e^{i(\delta_2 - \delta_1)} + (-s_2 + is_3)e^{-i(\delta_2 - \delta_1)}]$$

In this reexpressed form of the equation we see that the intensity is composed of seven different frequency components based on the retardance of the two added optical retarders:  $0, \pm \delta_2, \pm (\delta_2 + \delta_1)$ , and  $\pm (\delta_2 - \delta_1)$ . If the same material is used for both retarders, and the second retarder is twice as thick as the first, then these

seven frequency channels will be evenly spaced apart. By taking the fourier transform of the measured intensity pattern, we can easily see the seven separated frequency channels as seen in figure 12.

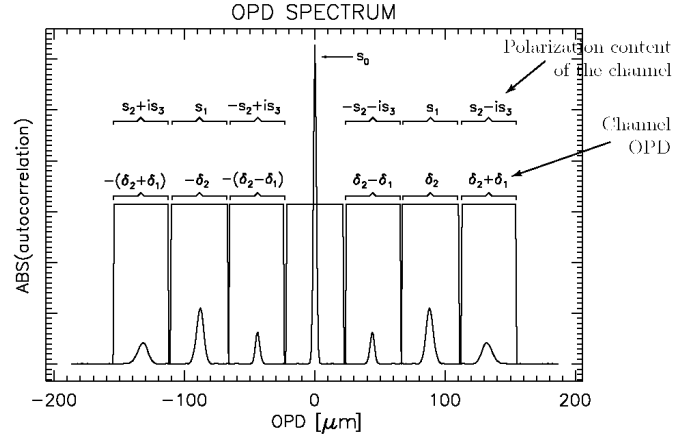


Figure 12: Plot showing the 7 frequency channels that compose the wavelength intensity function.

Each of these seven frequency channels correspond to a particular polarization state or a combination of polarization states. For example, the zero frequency channel is composed of just unpolarized light,  $s_0$ , while the  $\pm \delta_2$  frequency channels are only composed of light that is  $s_1$  polarized. To reconstruct the polarization data across the spectrum for a given stokes component, we must first select the desired frequency channel, multiply by an appropriate windowing function to isolate the channel, and then inverse fourier transform to see how that polarization state varies in wavenumber/wavelength. To reconstruct the  $s_2$  and  $s_3$  stokes components you must add or subtract data from the appropriate frequency channels before applying an inverse fourier transform.

It is the fact that the different stokes components encode modulations of the spectra at different frequencies, that allows us to reconstruct the spectral dependence of the four stokes components across spectrum.

When channeled spectropolarimetry is incorporated into a CTIS system, the imaging system is now able to determine the four stokes components for all the wavelength bands in addition to determining the spectra from each spatial location in a scene. The added polarization elements cause modulations in the spectra composing each of the diffraction orders. The same tomographic reconstruction techniques, as in a regular CTIS, are used to reconstruct these modulated spectra for each spatial position. The modulated spectra are then analyzed to reconstruct the four stokes components spectra for each of the spatial locations. Some examples of stokes spectrum reconstructions taken with the LWIR CTICS system are shown below.

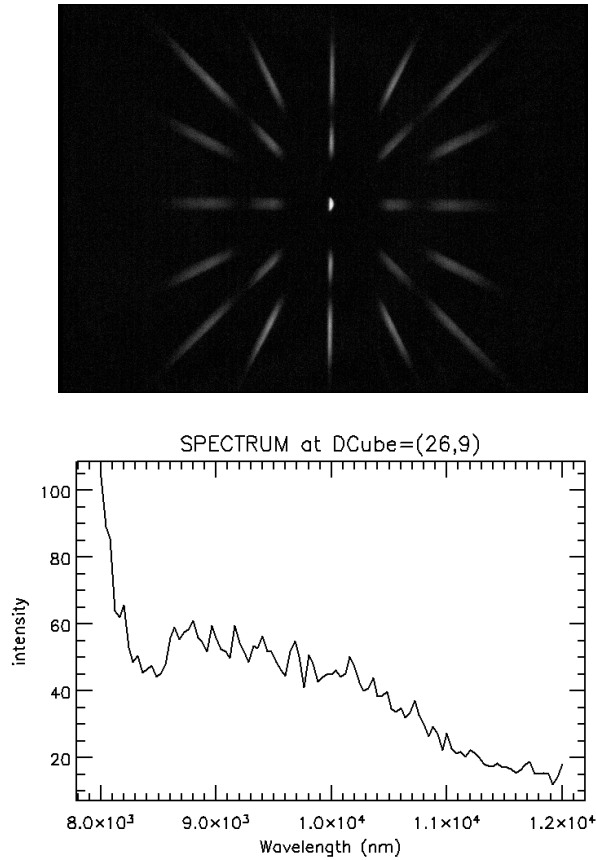


Figure 13: Unpolarized Blackbody Object; (top) Raw CTICS image, (middle) Reconstructed spectrum, (bottom) Normalized reconstructed Stokes spectra. Note that S1, S2, and S3 are all zero across the spectra as expected for an unpolarized object

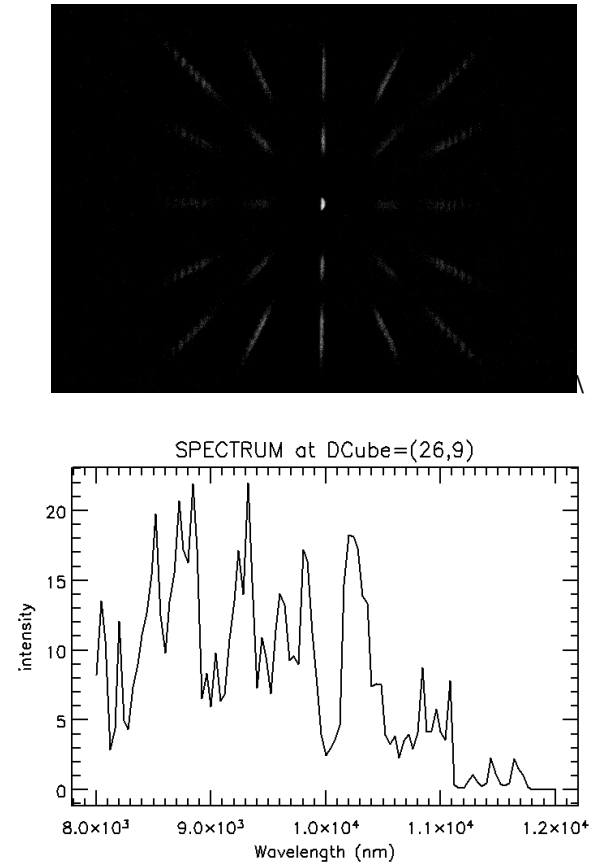


Figure 14: Vertically Polarized Blackbody Object; (top) Raw CTICS image, (middle) Reconstructed spectrum, (bottom) Normalized reconstructed Stokes spectra. Note that S1 is close to  $-1$  across the entire spectra, as expected, while S2 and S3 are all close zero across the spectra

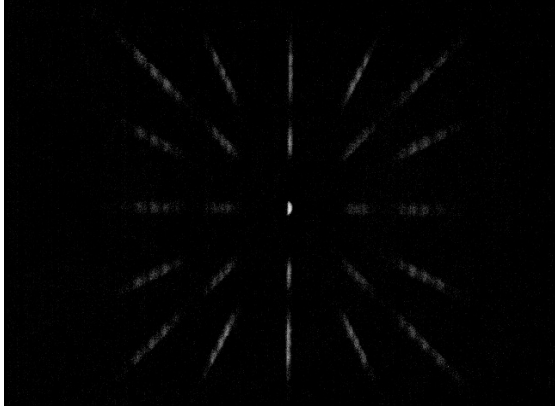


Figure 15: Blackbody Polarized at 45 Degrees; (top) Raw CTICS image, (middle) Reconstructed spectrum, (bottom) Normalized reconstructed stokes spectra. Note that S2 is 1 across the entire spectra, as expected, while S2 and S3 are both close zero across the spectra

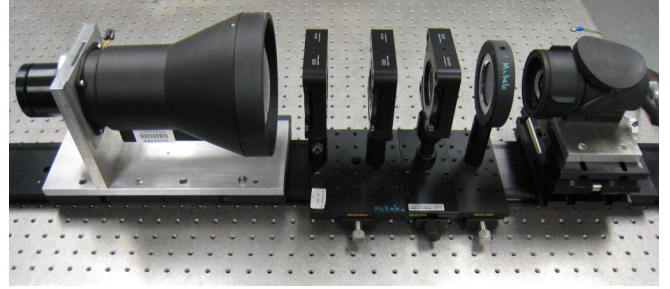


Figure 16: Photo of the assembled LWIR CTICS system. Components include off the shelf LWIR lenses, crystal retarders, wire grid polarizer, GaAs CGH, and a 640x480 resolution uncooled silicon microbolometer LWIR camera.

## CONCLUSIONS

The results from the LWIR CTICS demonstrate that snapshot imaging spectropolarimetry in the 8 to 12 micron region works. Using a combination of Computed Tomographic Imaging Spectrometry (CTIS) and channeled spectropolarimetry, the system is capable of simultaneously recording both the spectral and polarimetric signatures of all the spatial locations/targets in a scene with just a single integration period of a camera. The system contains no moving parts and collects all of its data in a single snapshot. This snapshot capability makes it uniquely suited for observing and characterizing the spectral and polarimetric features of quick events or fast moving objects without the associated scanning artifacts found in conventional imaging spectrometers and polarimeters.

## ACKNOWLEDGEMENTS

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